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Simulation of Thermal Effects of Engineering Objects in the Arctic Regions on the Permafrost Boundaries

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Abstract. The paper discusses a mathematical model for describing heat distribution in the surface layer of soil from various sources of heat, or cold, which, together with seasonal climatic changes, form unsteady thermal fields in the soil. The developed algorithms are focused on high-performance computers and were used in the design of various oil and gas fields located in permafrost zone. The main attention is paid to adequate setting of boundary conditions and maximum consideration of various parameters, including technical characteristics of engineering objects, climatic conditions and soil lithology in the field of modeling thermal fields. The presented numerical calculations show the possibility of using these models and algorithms for forecasting of the development of thermal processes in the soil. Minimization of heat effect of the systems inserted into permafrost will avoid accidents, in particular, at oil and gas fields related to the changes in temperature of the soil, and increase the stability of the building with pile foundations. In the paper the possibility of the heat impact compensation in permafrost is discussed.

INTRODUCTION

Permafrost occupy about 25 % of the total land area of the globe and is highly susceptible to external influences caused by human activity and climate change [1, 2]. Most engineering structures and buildings in the permafrost zone use the principle of preserving the frozen state of the soil. For these purposes, various options for thermal insulation of the soil surface, piles, which are the foundation for residential buildings, cooling devices for thermal stabilization of the soil [3, 4, 5, 6] and other options for preventing permafrost degradation, are used. Thawing permafrost can lead to serious accidents and the destruction of buildings. For example, damage to production wells in the northern oil and gas fields due to permafrost processes leads not only to large financial losses, but also to the environmental disasters.

The main feature of permafrost soils is that the particles are firmly cemented by ice structures, and the mechanical properties essentially depend on temperature. In addition, such soils are unstable and significantly influenced by both changes in climatic conditions and human intervention [7, 8]. Various technical systems [9, 10] used in oil and gas fields, and engineering structures [11, 12, 13] are sources of heat that affect permafrost, which due to thermal effects lose their strength properties.

For description of non-stationary thermal fields of the technical systems in the frozen soil there are developed various mathematical models, taking into account the most important climatic factors. Studying thermal fields on the surface of the soil from underground pipelines in view to determine the damages [14, 15], it was found that the solar radiation has a great influence on the formation of thermal fields in the upper layer of the soil. Therefore, in studying non-stationary fields propagation in the soil from various technical systems used in the northern oil and gas fields [3, 12], solar radiation was also taken into account.

Numerical calculations of all technical systems affecting permafrost require significant computational power and call parallel technologies [16, 17, 18].

In permafrost soils, it is possible to determine two main zones: first zone is an accumulation layer, in which the soil temperature is constantly changing during the year (Active Layer Thickness or ALT), second zone is relatively stable and has the same temperature over many years [19].

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Numerous building failures in permafrost regions are related to changes in permafrost due to poor design, and to poor maintenance of buildings, which are more powerful factors than the natural change in permafrost temperature. As long as the mean annual temperature remains below 0°C, the permafrost protection doesn't need no application of artificial refreezing. On summer, as a result of positive temperatures and solar radiation effect, there is a seasonal thawing of the upper layer, on winter there is a reverse freezing process. Thawing of ice-saturated rocks due to warming or various technogenic impacts could be accompanied by subsidence of the earth's surface and the development of thermokarst, leading to destruction of the engineering structures [1, 2, 13].

In order to reduce permafrost thawing around there are used different insulation materials, and various devices to cool the soil, such as seasonal cooling devices (SCDs) [3].

In this paper the effect of the heat source (a well or a pipe) on the surrounding frozen soil, taking into account various conditions (the presence of riprap and cooling devices) are compared. In the course of numerical experiments, the effect of such sources of heat and cold on ALT and the deeper layers is observed.

MODEL OF HEAT DISTRIBUTION IN PERMAFROST

The basic human influences on permafrost consists of a combination of disturbance of the structure of the upper layers of the soil and thermal impact of different technical systems.

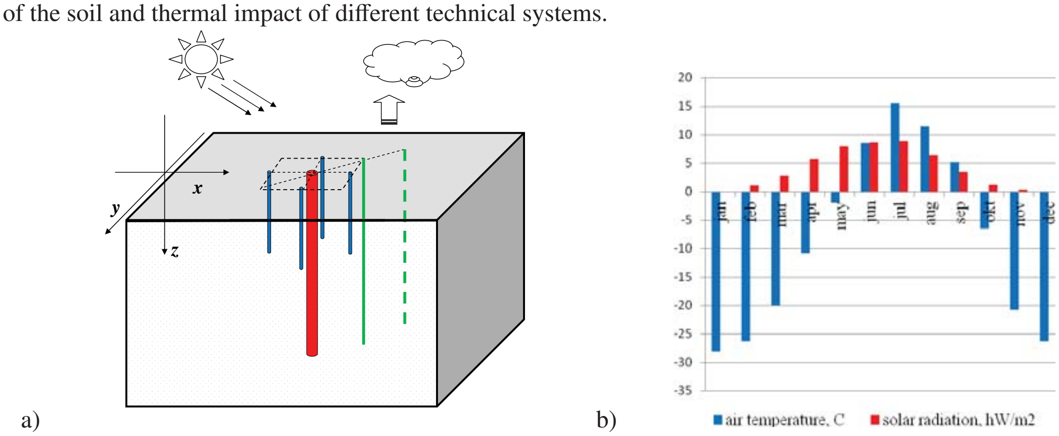


FIGURE 1. a) — basic scheme of simulated area Ω, b) — basic climatic prameters: air temperature, °C, and solar radiation, hW/m^2.

To simulate the processes of heat distribution in permafrost soil a three-dimensional diffusivity equation with non-uniform coefficients including localized heat of phase transition is considered. Following [8, 20, 21] this approach allows to solve the problem of Stefan type, without the explicit separation of the phase transition in 3D area Ω (Figure 1a). The equation has the form

$$\rho\Big(c_\nu(T) + k\delta(T - T^*)\Big)\frac{\partial T}{\partial t} = \nabla\left(\lambda(T)\Delta T\right), \tag{1}$$

with initial condition

$$T(0, x, y, z) = T_0(x, y, z). \tag{2}$$

Here $T_0(x, y, z)$ is initial ground temperature at time $t = 0$, ρ is density [kg/m^3], T^* is temperature of phase transition [K],

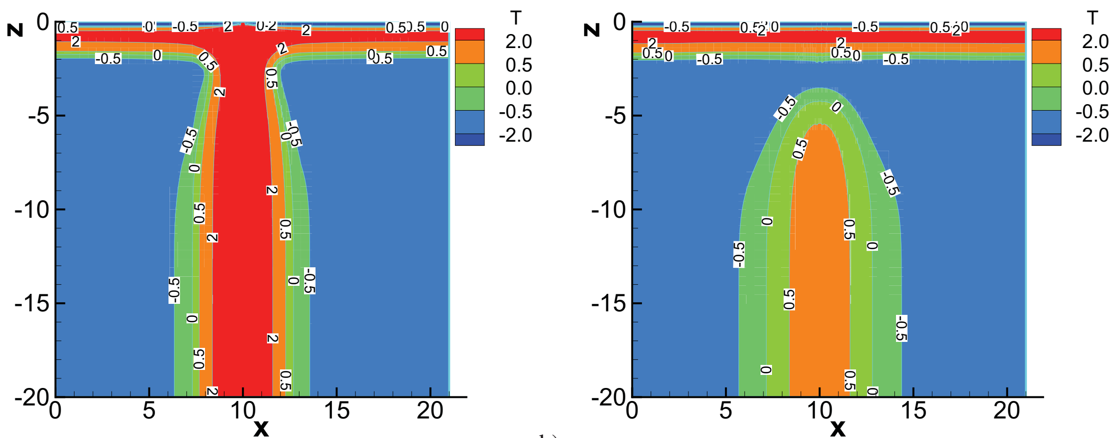
$$c_\nu(T) = \begin{cases} c_1(x, y, z), & T < T^*, \\ c_2(x, y, z), & T > T^*, \end{cases} \text{ is specific heat [J/(kg K)],}$$

$$\lambda(T) = \begin{cases} \lambda_1(x, y, z), & T < T^*, \\ \lambda_2(x, y, z), & T > T^*, \end{cases} \text{ is thermal conductivity coefficient [W/(m K)],}$$

$k = k(x, y, z)$ is specific heat of phase transition, δ is Dirac delta function.

Balance of heat fluxes at the surface $z = 0$ taking into account climate data (Figure 1b) defines the corresponding nonlinear boundary conditions

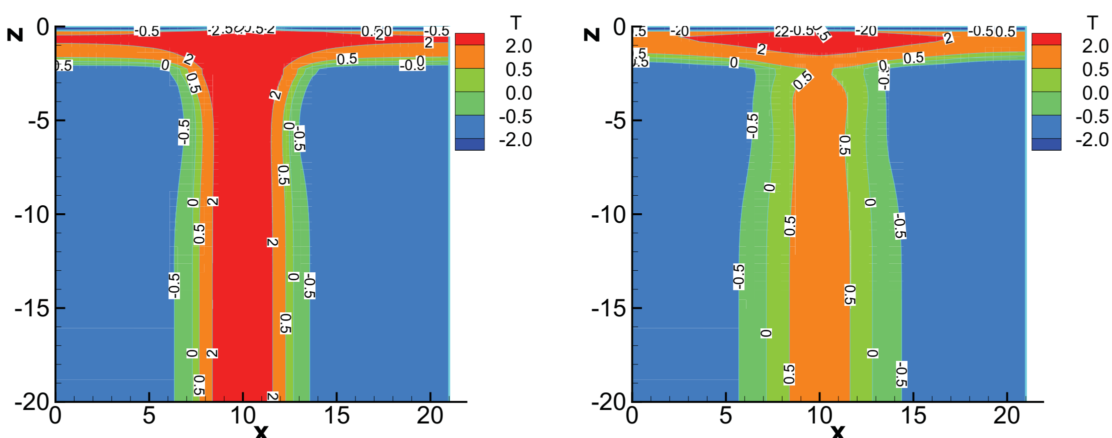
$$\gamma q + b(T_{air} - T(x, y, 0, t)) = \varepsilon\sigma(T^4(x, y, 0, t) - T^4_{air}) + \lambda \frac{\partial T(x, y, 0, t)}{\partial z}. \tag{3}$$



a) b)

FIGURE 2. Temperature fields for the 1st case: no riprap and no SCD. a) and b) are the fields after of 2 years of heating and further 1 year of cooling down, respectively.

To determine the parameters in boundary condition (3), an iterative algorithm is developed that takes into account the geographic coordinates of the area, lithology of soil and other features of the considered location [8, 22].



a) b)

FIGURE 3. Temperature fields for the 2nd case: 2.5 m of riprap and no SCD. a) and b) are the fields after of 2 years of heating and further 1 year of cooling down, respectively.

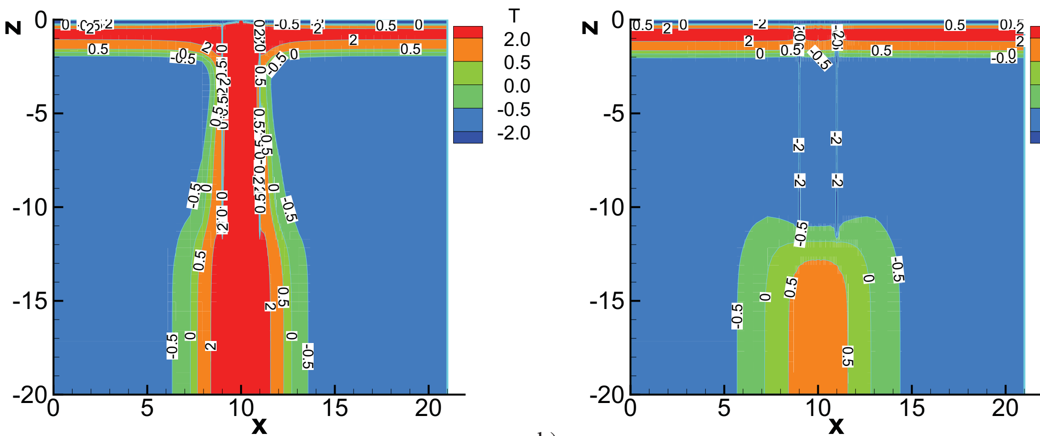
Let consider a pipe (the surfaces of this well is tube $\Omega_0(x, y, z)$ with temperature $T_0(t)$ and n seasonal cooling devices Ω_i with temperature $T_i(t)$, $i = \overline{1, n}$, which are included in Ω. These surfaces suppose to be inner boundaries with the conditions

$$T\Big|_{\Omega_i} = T_i(t), \quad i = 0, \ldots, n. \tag{4}$$

The computational domain is a three-dimensional box Ω, where x and y axes are parallel to the ground surface and the z axis is directed downward. We assume that the size of the box Ω is defined by positive numbers L_x, L_y, L_z: $-L_x \le x \le L_x$, $-L_y \le y \le L_y$, $-L_z \le z \le 0$.

At the boundaries of the domain the boundary conditions are given

$$\frac{\partial T}{\partial x}\Big|_{x=\pm L_x} = \frac{\partial T}{\partial y}\Big|_{y=\pm L_y} = 0, \quad \frac{\partial T}{\partial z}\Big|_{z=-L_z} = 0. \tag{5}$$



a) b)

FIGURE 4. Temperature fields for the 3rd case: no riprap and 4 SCDs. a) and b) are the fields after of 2 years of heating and further 1 year of cooling down, respectively.

On the base of ideas in [20, 21] a finite difference method is used with splitting by the spatial variables in three-dimensional domain to solve the problem. We construct an orthogonal grid, uniform, or condensing near the ground surface or to the surfaces of internal boundaries Ω_i.

The original equation for each spatial direction is approximated by a locally additive implicit scheme, and to solve a system of linear differential algebraic equations the combination of the sweep and Newton method is used. Solvability of the same difference problems approximating (1)–(5) is proved in [23].

NUMERICAL RESULTS

Let consider a technial system inserted into a permafrost soil. The basic thermal parameters of the soil are in the following: thermal conductivity is 1.82 and 1.58 W/(m K), volumetric heat is 2130 and 3140 kJ/(m^3 K) for frozen and melted soil, respectively; volumetric heat of phase transition is $1.384 \cdot 10^5$ kJ/(m^3 K). The permafrost temperature lower than the area of influence of seasonal changes (lower than 10 meters) is -0.7°C. In Figure 1 the basic thermal units and the monly average data are shown for the considered area.

A heat source inserted into frozen soil is supposed to be a vertical warm pipe (Figure 1a, the red pipe) with the temperature 20°C, 4 SCDs may accompanie the pipe at the distance of 1 m. (the blue pipes).

Size of the computational area are L_x=L_y=L_z=20m, SCD's deep iz 11.5m, diameter is 0.057 m. The pipe diameter is 0.178 m with a cement shell with 124 mm of thickness. Numerical grid sizes had varied from 91x91x51 to 191x191x151, time step is 24 hours. The basic climatic parameters are presented in Figure 1b.

Stabilization of soil is primarily due to the restriction of seasonal effects of changes in air temperature and solar radiation intensity. To do this, as a rule, multi-layer ripraps are used. For example, we will use the riprap with three

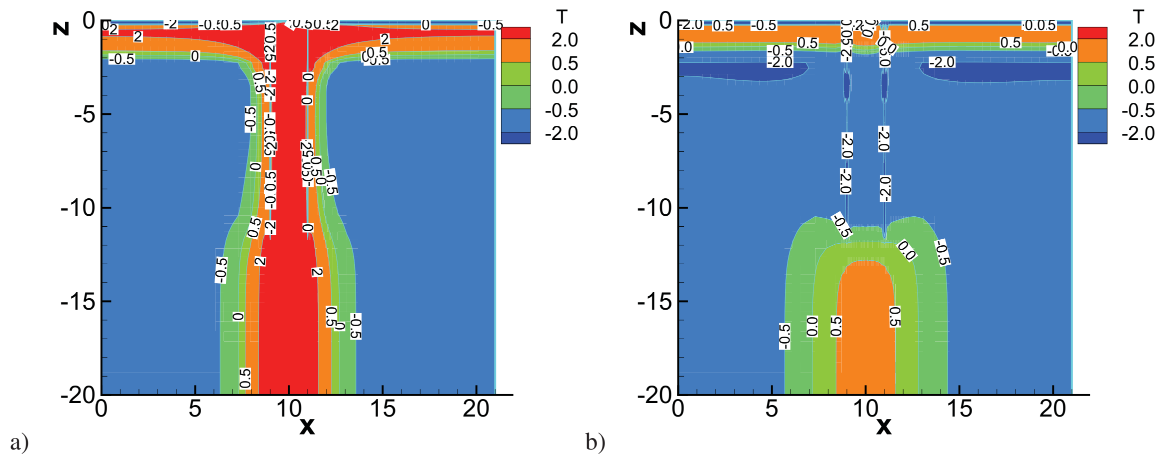


FIGURE 5. Temperature fields for the 4th case: 2.5 m of riprap and 4 SCDs. a) and b) are the fields after of 2 years of heating and further 1 year of cooling down, respectively.

layers: 0.3m of concrete slab, 2m of sand, 0.2m of foam. Also, on winter a system of seasonal cooling devices may be used for soil refreezing.

Four basic cases of the equipment will be considered.
1st. No riprap and no SCDs.
2nd. 2.5 m of riprap and no SCDs.
3rd. No riprap and 4 SCDs.
4th. 2.5 m of riprap and 4 SCDs.

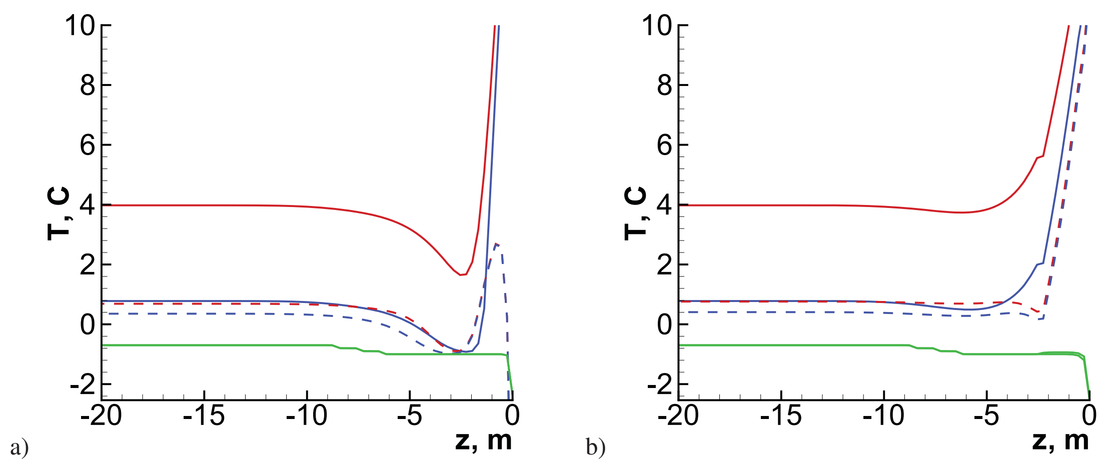


FIGURE 6. Profiles of the temperatures in the control points after of 2 years of heating (red lines) and further 1 year of cooling down (blue lines). a) and b) — for the 1st and 3rd cases, respectively.

In Figures 2–5 thermal fields arount the pipe are presented. The simulations suppose that the pipe has been warmed with the temperature 20°C for 2 years, and then is cooling down during 1 years. Figures 2a–5a show the temperature after two years of the pipe warming, and Figures 2b–5b show the temperature after 1 years of passive cooling. The figures correspond to the end of september, the most warm period in the soil. We may see the ALT thickness as the upper front of thawing with positive temperature.

Figure 2 shows the temperature field for the 1st case. The front of thawing (0°C) from the pipe continues to propagate even during the cooling fase. The zone of unstable soil (between -0.5 and 0°C) is coming wider. Uncoated soil is affected by annual day surface temperature changes. The influence of winter cold is rather active and is the most important factor of the temperature field forming in upper layers of permafrost.

In Figure 3 the temperature field for the 2nd case are presented. The riprap presence accumulates the heat from the heat source, especially in the upper layers of the soil. ALT and front of thawing from the pipe are combined. It also prevents the free heat dissipation and cooling of permafrost under the riprap on winter. The thermal trace under the riprap is longer and unchanged.

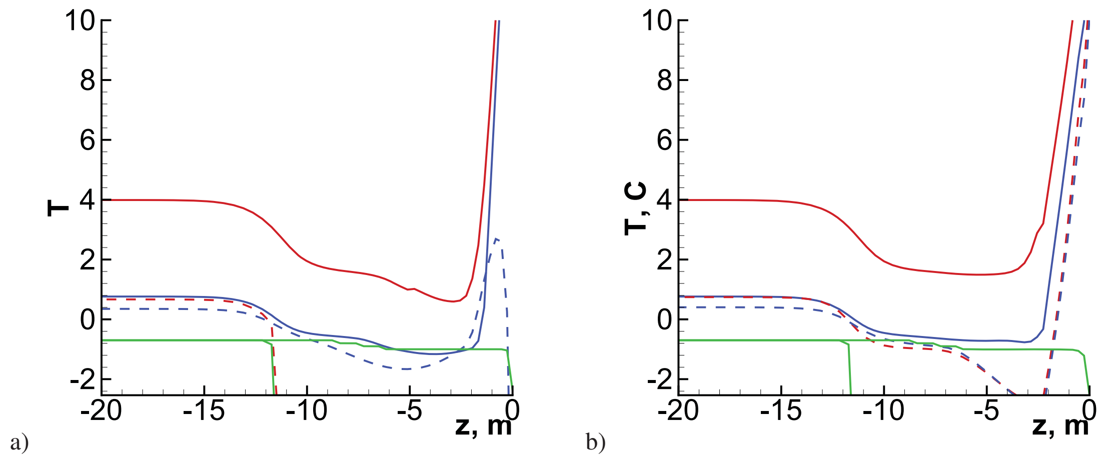


FIGURE 7. Profiles of the temperatures in the control points after of 2 years of heating (red lines) and further 1 year of cooling down (blue lines). a) and b) — for the 2nd and 4th cases, respectively.

Figure 4 shows the temperature field for the 3rd case: uncoated soil with SCDs. The SCDs application allows to restrain the heat propagation from the pipe, but the zone of SCDs influence is restricted by the device depth. Also the SCDs allow to return the soil to the frozen state.

In Figure 5 the temperature field for the 4th case are presented. A combination of riprap and SCDs allows to accumulate the cold and deliver it to the deeper layers of soil.

Figures 6 and 7 show the temperature at the vertical lines (see Figure 1a, the green lines). The most close to the heat source control piint is at the distance 1.2 m (the solid lines), and the second control point at the distance 2.4 m (the dashed lines). The green profiles in Figures 6 and 7 correspond to the initial soil temperature.

Figure 6 shows 1st and 3rd cases, when SCDs are not inserted. The temperature is still positive after the heat source has been removed, except for the small area at the deep of ALT bottom. Figure 7 shows 2nd and 4rd cases, when 4 SCDs are used for refreezig the soil. The temperature is closed to initial in the impact zone of SCDs.

CONCLUSION

Permafrost had formed under the influence of natural cooling and compose the relict soil layers, isolated from the external settings. Objects built by humans in permafrost zones have a significant thermal impact on the environment, which contributes to the destruction of permafrost soils as well as waterlogging of the soil. Intervention into permafrost, especially at great depths, cannot be compensated for by the surrounding environment. Without additional measures, the restoration of the natural temperature background is impossible even after removing the heat sources. The areas of thawing can occupy larger volumes, initiating soil instability. Restoring the temperature of permafrost soils, the bearing capacity is possible with the use of special methods for refreezing, for example, using, seasonal cooling devices.

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